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Numerical prediction of the low-velocity impact damage and compression after impact strength of composite laminates

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Abstract. Low-velocity impact damage can drastically reduce the residual mechanical properties of the composite structure even when there is barely visible impact damage. The ability to computationally predict the extent of damage and compression after impact (CAI) strength of a composite structure can potentially lead to the exploration of a larger design space without incurring significant development time and cost penalties. A three-dimensional damage model, to predict both low-velocity impact damage and compression after impact CAI strength of composite laminates, has been developed and implemented as a user material subroutine in the commercial finite element package, ABAQUS/Explicit. The virtual tests were executed in two steps, one to capture the impact damage and the other to predict the CAI strength. The observed intra-laminar damage features, delamination damage area as well as residual strength are discussed. It is shown that the predicted results for impact damage and CAI strength correlated well with experimental testing.

1. Introduction

Composite materials are increasingly used in the aerospace and automotive industries due to their high specific stiffness and strength, nevertheless, the susceptibility to damage from low-velocity impact event (*i.e.* falling tools, runway debris *etc.*) is one of the major design concerns. When subjected to impact loading, the composite structure can be degraded through various failure mechanisms including matrix cracking, fibre breakage and delamination. Impact damage can dramatically reduce the residual mechanical properties of the structure even with barely visible impact damage. It is therefore essential to develop a reliable tool for the prediction of the impact damage process and evaluation of corresponding residual strength.

A limited number of studies on predicting the CAI strength of damaged composite structures are available in the literature. Uda *et al.* [1] investigated failure mechanisms of impact-damaged UT500/Epoxy and AS4/PEEK CFRP laminates subjected to compression fatigue. Ghelli and Minak [2] conducted CAI tests on thin laminates, taking into account sub-laminate buckling under compression. Most of the current work was performed on composites with predefined delaminations or imperfections [3]. A model where both virtual tests (impact and CAI) are performed on composite sandwiches can be found in Davies *et al.* [4]. González *et al.* [5] proposed a 3D FE model with inter-laminar and intra-laminar damage using a rigorous thermodynamic framework for drop-weight



impact and CAI test simulations and studied the effect of different stacking sequences. The numerical results showed large oscillations compared to experimental data and took 12-15 days to execute, which is very computational expensive. Rivallant *et al.* [6] presented a numerical model for impact and CAI using the interface element between neighbouring volume elements to model intra-laminar matrix cracking, cutting the run-time to 12-15 hours.

The present work, based on an extension of a previous model by Falzon *et al.* [7-10], was used to simulate both impact and CAI. The results of the simulation are compared with experimental data. The observed intra-laminar damage features, as well as residual strength prediction are discussed. It is shown that the predicted results for impact damage and CAI strength correlated well with experimental testing.

2. Materials and Methods

2.1. Composite Damage Model

The degraded damage model captures failure modes in the forms of matrix cracking, fibre breakage and delamination as shown in Figure 1. Details of the damage model may be found in [7-9] which accounts for these damage modes in a laminate subjected to a 3D stress state.

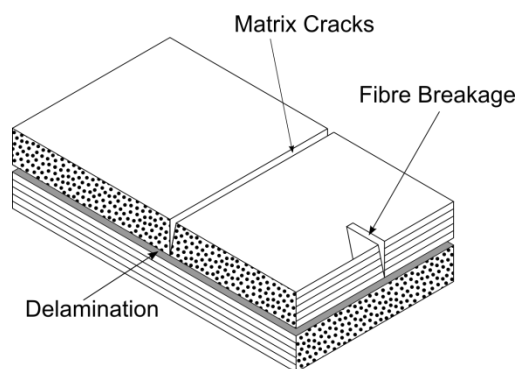


Figure 1. Damage Modes of Composite Laminates.

2.2. CAI Test Model

In this context, the test model is the same as in reference [6]. The virtual tests set up in ABAQUS 6.12/Explicit were executed in two steps, one to capture the impact damage and the other to predict the CAI strength. The laminate plate measured 100 mm × 150 mm × 4.16 mm, simply-supported within a 'picture frame' with a 75 mm × 125 mm effective test section (Figure 2). The T700/M21 composite plate was impacted with 29.5 J of impact energy using a hemi-spherical, 16 mm diameter, 2 kg impactor.

Once the simulation of the impact process was completed, the CAI simulation was subsequently carried out by constraining the out-of-plane direction of the nodes in contact with the picture frame. The planar displacements were also constrained for all nodes at the bottom of the laminate in contact with the support. Although the CAI test is essentially quasi-static (0.5mm/min), it was simulated by using ABAQUS/Explicit to avoid the severe convergence difficulties encountered with implicit analysis. The loading speed was chosen at 3.75 m/min to reduce the CPU running time. Selective mass scaling (scales only elements whose stable time increment is below the value assigned to a time increment of 1e-07) was also employed in the CAI process to achieve a reasonable run time.

2.3. Material Properties

Material properties were obtained from the literature [6], given by Table 1. The c_i ($i = 1,2,3$) describe a quadratic constitutive shear stiffness curve obtained using a least square fitting method [11]. Γ_{ii}^{Mode} ($i = 1,2$ and Mode = Tensile, Compressive) denote the intra-laminar fracture toughness in the

longitudinal (11) and transverse (22) directions, and G_I and G_{II} are the inter-laminar fracture toughness for mode I and mode II.

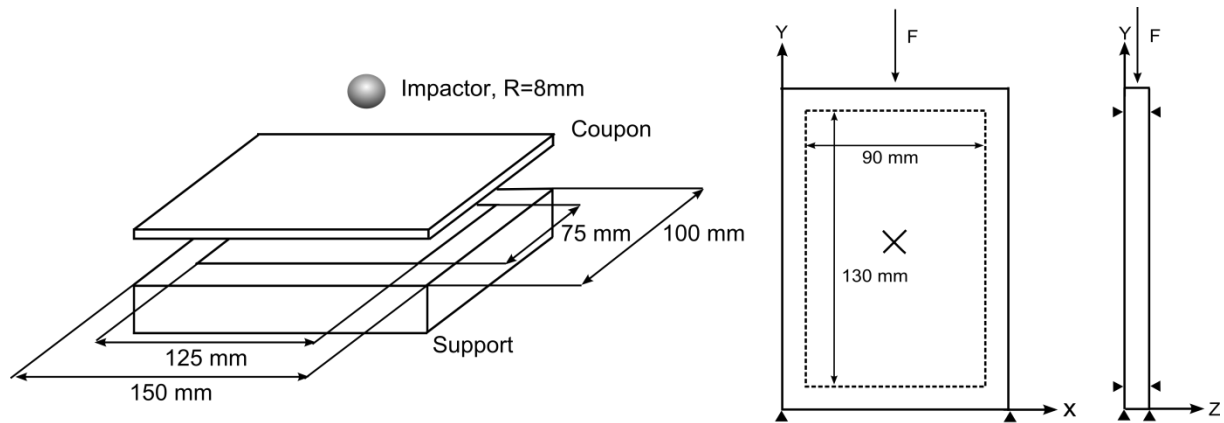


Figure 2. Impact test and CAI setup with the boundary condition.

Table 1. Material Properties of T700/M21 composite.

Property	Values	Property	Values	Property	Values
E_1	130 GPa	X^C	1250 MPa	Γ_{22}^C	1.6 N/mm
$E_2 = E_3$	7.7 GPa	Y^T	60 MPa	$\Gamma_{12,C} = \Gamma_{23,C}$	1.6 N/mm
$\nu_{12} = \nu_{13}$	0.3	Y^C	290 MPa	G_I	0.5 N/mm
ν_{23}	0.35	S_{12}	110 MPa	G_{II}	1.6 N/mm
$G_{12} = G_{13}$	4.8 GPa	Γ_{11}^T	133 N/mm	c_1	37833 MPa
G_{23}	3.8 GPa	Γ_{11}^C	10 N/mm	c_2	16512 MPa
X^T	2080 MPa	Γ_{22}^T	0.5 N/mm	c_3	2334.3 MPa

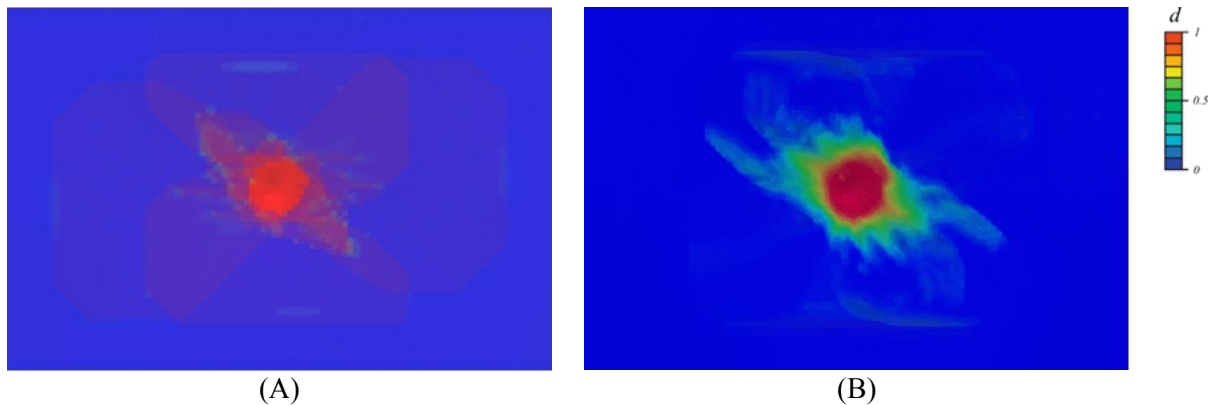


Figure 3. (A) Matrix Damage, and (B) Delamination of 29.5 J

3. Results

3.1. Impact Matrix Damage

The intra-laminar damage model allowed the various forms of intra-laminar failure to be investigated as the impact event progressed. Figure 3 shows the superposition of the matrix cracking throughout the layers. Matrix cracking was found to be the dominant form of intra-laminar failure. Matrix damage mainly occurred in the centre part of the impact area with a symmetric distribution similar to that reported in [12]. It is clearly that the matrix damage propagated from the centre and towards the boundary of “picture frame”. The peanut shaped damage contour for the delamination can be observed in Figure 3 which matches well with the experimental results from C-scans [6], though the size of the damage area is smaller. These could be attributed to the fact that the experimental results are the combination of the matrix damage and delamination.

3.2. Force-Time and Force-Displacement Curves

In Figure 4A, the experimental results of force-time history are not available and the numerical results show the overall impact response. The load oscillation is an artefact of the numerical method due to matrix failure and delamination failure. Upon contact with the laminate, the impactor force increased gradually with some fluctuation before it reached the peak load when impact velocity was zero. From this stage onwards, the force began to drop until it reached zero, during which the impactor rebounded. The force-displacement history of the impactor correlated well with the experimental results shown in Figure 4B. The initial contact response and maximum displacement of the impactor are captured accurately compared to experimental results [6].

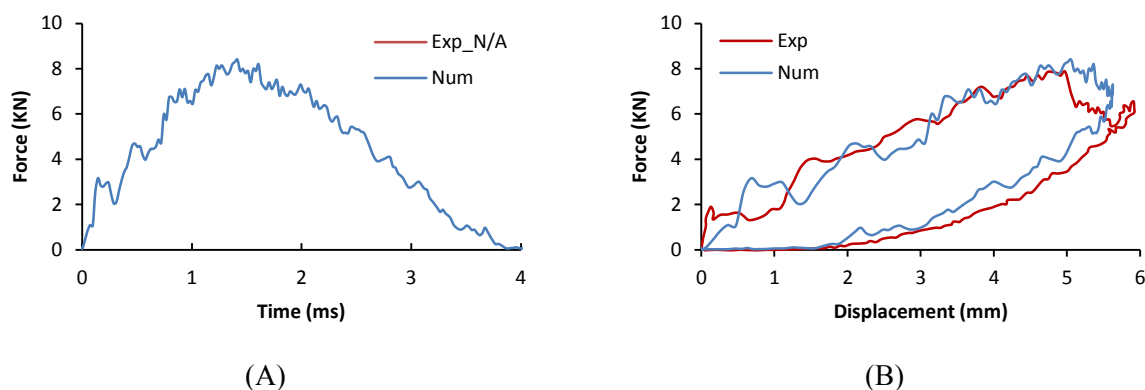


Figure 4. (A) Force-Time History, and (B) Force-Displacement History of 29.5 J

3.3. CAI Matrix Damage

The extensive matrix damage of the CAI test under impact energy of 29.5 J is shown in Figure 5. Most matrix damage occurred at the centre line through the indented zone. The CAI test process from (A) to (D) indicated that new matrix damage initiated from the two outer edges, possibly due to free edge effects, and propagated towards the damaged centre of the panel. Sub-laminate buckling is also observed in (E).

3.4. CAI Stress-Displacement Curve

CAI experimental results in terms of the stress-displacement relationship were only available for the 29.5 J impact case [6]. Applied stress versus end displacement curve in Figure 6 shows that good correlation was achieved between the experimental and numerical results, with the ultimate load being predicted to within 9.3% of the experimental results.

Another model (undamaged line) was executed with no impact damage which shows that the damaged panel failed at 40% of the load carried by the pristine panel.

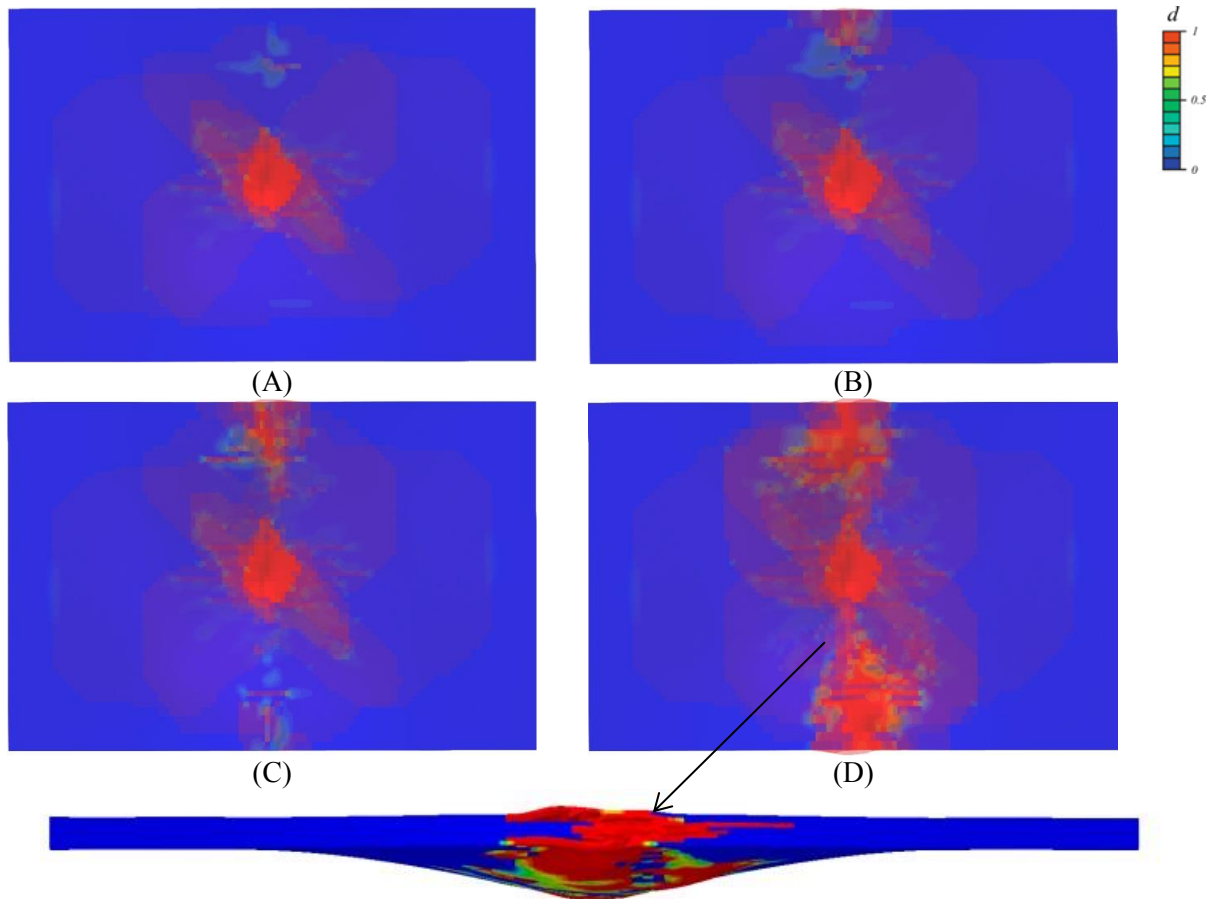


Figure 5. CAI Matrix Damage, (A) 14 ms, (B) 15 ms, (C) 16 ms, (D) 22 ms, (E) Side view.

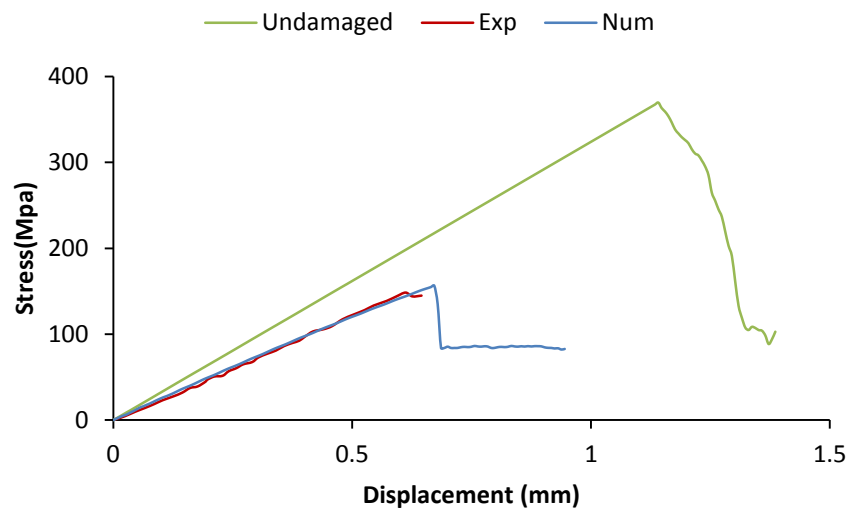


Figure 6. CAI stress-displacement curve.

4. Conclusions

Through the data obtained from the force-displacement and damage parameters, the impact test successfully demonstrated that the model can capture intra-laminar and inter-laminar damage well – both qualitatively and quantitatively – for the given impact energy. Concerning the CAI simulation, the observed intra-laminar damage features, as well as residual strength were accurately predicted. This was achieved without the need to calibrate the input parameters. The current model has proved to be a reliable and efficient tool to numerically predict the CAI strength.

Future work will focus on extending this computational damage model to capture high energy crush events. This will enable the virtual testing of bird strikes and assessment of crashworthiness of aero-structures.

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